Chapter 3
Geostatistical Resources and Tools

Since the mid-1970's, a myriad of texts and articles have been published that are either totally dedicated to geostatistical methods or discuss geostatistics in detail. Numerous computer programs and software packages on geostatistics and kriging accompany many of these texts. Although only a few of these resources will be briefly described in this ETL, their lists of references can provide the interested reader a path to other geostatistical topics or software not specifically covered in the resources.

3-1. Texts on Geostatistics

a. The geostatistical texts presented in this section can be classified into two broad categories: instructional texts or reference texts. For one who is delving into geostatistics for the first time, Clark's (1979) book is a starting point. Simple explanations of the basic kriging techniques are applied to an example data set. A more advanced treatment of the kriging techniques is described by Isaaks and Srivastava (1989). This textbook presents a detailed discussion of many of the background statistical tools and concepts needed in geostatistical applications, including histograms and distributions (univariate and bivariate), sampling, correlation, and spatial continuity. The text also discusses how to treat the subtleties of kriging using three data sets as examples. As well as being instructional, the book also can be used as a reference.

b. Texts by Cressie (1991) and Journel and Huijbregts (1978) describe the tools of geostatistics, but also include a comprehensive theoretical background on the techniques. Cressie's (1991) text is a treatment of spatial processes in general and reviews a wide range of statistical techniques in the analysis and stochastic modeling of spatial data. There is a four-chapter section on geostatistics, with a complete discussion of variogram estimation, kriging (including universal kriging), intrinsic random functions, and comparisons of kriging to other spatial prediction techniques. The text is written from a statistician's point of view and is, in places, written at a fairly high level mathematically. It nevertheless contains numerous examples and illustrations using real-world data. Journel and Huijbregts (1978) maintain a mining-geological perspective. Two other texts written by statisticians that present general treatments of spatial processes, but that lack detailed discussions of kriging, are Cliff and Ord (1981) and Ripley (1981).

c. David's (1977) text was the first extensive discussion of geostatistics and kriging in mining applications, and the discussion is presented from a practitioner's viewpoint. Its value as reference material derives from the many specific mining applications and results. A broad statistics text with a bent toward geological applications (Davis (1986), serves as a reference for standard statistical procedures needed in geological applications of geostatistics. A book by Bras and Rodriguez-Itrube (1985) that discusses a range of techniques for stochastic modeling in the field of hydrology includes a chapter on applications of kriging. There is a fairly complete mathematical development of kriging with details of an application to predict mean areal precipitation. In a paper prepared for the U.S. Environmental Protection Agency, Journel (1993) discusses geostatistics as it relates to environmental science. Finally, Olea (1991) presents a useful glossary of geostatistical terms.

3-2. Useful Journals

The journal *Mathematical Geology* by the International Association for Mathematical Geologists reports new developments in the theory and application of kriging. Although many of the articles present new applications of kriging tools, many also are dedicated to the derivation of statistical properties of the variogram, kriging estimation, and cross-validation results. Journals such as *Water Resources Research*, published by the American Geophysical Union, and *Groundwater*,

published by the Association of Groundwater Scientists and Engineers, contain articles describing special applications of kriging techniques in the environmental arena. *Water Resources Research* tends to contain articles that are highly theoretical. Other journals that may contain information addressing geostatistics are the *Journal of Environmental Engineering*, published by the American Society of Civil Engineers; *Stochastic Hydrology and Hydraulics*, published by Springer International, and the *North American Council on Geostatistics*, published by the Colorado School of Mines.

3-3. Software

a. The geostatistics software described in this section is limited to a few readily available public domain packages that are executable at least on the DOS and sometimes on the UNIX platforms. There are several commercial packages that are being marketed, but these will not be reviewed in this ETL. It is beyond the scope of this ETL to acquire and evaluate commercial packages; however, a matrix-like table (Table 3-1) has been included. The table addresses each of the software packages described in this ETL and also may serve as a reference guide to other software packages.

b. Some of the earliest interactive kriging software offered as a package was developed by Grundy and Miesch (1987). Overall, this general statistics package (STATPAC) contains a series of programs that can handle two-dimensional kriging, including universal kriging. The package has capabilities for data transformations, variogram analyses, cross-validation, and univariate statistics (Table 3-1). Graphics in the package are limited to simple line-printer plots of the sample variogram points and data maps. The menu-driven package includes a tutorial using all of the kriging routines. The package is distributed with not all, but most source codes and, therefore, can be modified by the user if desired. All two-dimensional kriging routines can be executed from the command line, which provides users with the opportunity for batch processing.

c. The geostatistical environmental assessment software know as GEO-EAS (Englund and Sparks 1991) also is an interactive, menu-driven kriging software package for performing two-dimensional kriging. It has no direct provisions for universal kriging (Table 3-1). GEO-EAS does have an advantage over STATPAC in its enhanced graphics capabilities, which are useful in the interactive fitting of theoretical variograms to sample variogram points. In addition, in the computation of the sample variogram points, GEO-EAS allows for variable bin sizes, the use of which will be further discussed in Chapter 4.

d. STATPAC and GEO-EAS were originally developed for the personal computer. Since then, versions of GEO-EAS have been developed for some types of work stations. The kriging routines in STATPAC have not been adapted to work stations.

e. A third software package, the geostatistical software library known as GSLIB (Deutsch and Journel 1992), is a suite of programs developed over the years at Stanford University, Stanford, CA. It is presented as a collection of routines that are machine-independent (Table 3-1) and are intended to be used as a modular concept. The package is distributed as a suite of FORTRAN source codes that need to be compiled. Use of GSLIB requires a relatively high level of familiarity with geostatistics for its efficient use. As in the previous two software packages, GSLIB handles variogram analysis and kriging techniques (Table 3-1). Two of its primary advantages over the other two packages are its simulation techniques and ability to analyze three-dimensional data sets. Such techniques are useful especially in estimating potential extreme outcomes in a geostatistical analysis.

f. The Department of Defense Groundwater Modeling System (GMS) is a fourth software package that has kriging capabilities. GMS is a windows-based integrated modeling environment for site characterization, groundwater flow and transport modeling, and visualization of results. The GSLIB software has been implemented within

GMS to facilitate two- and three-dimensional kriging and interactive variogram modeling. GMS also provides comprehensive visualization techniques as well as other interpolation techniques that can be used as alternatives to kriging. The GMS system was developed for the Department of Defense by the Brigham Young University Engineering Computer Graphics Laboratory. GMS may be obtained from the U.S. Army Groundwater Modeling Technical Support Center, (U.S. Army Engineer Waterways Experiment Station, Vicksburg MS 39180).

g. A final note concerning geostatistical software and literature is that there can be differences in jargon or notation. These differences may cause some initial confusion if users or readers do not pay careful attention to the jargon or notation. For example, some authors may wish to use the term “semi-variogram” rather than “variogram”; others may express random variables as other than Z as has been done in this ETL, and it is common for different software to have different references for directional angles when discussing anisotropy.

Table 3-1
Geostatistical Software Characteristics

Characteristic	STATPAC	GEO-EAS	GSLIB	GMS2.0
Operating system	DOS	DOX/UNIX	Independent (requires FORTRAN compiler)	WINDOWS 95 UNIX
Menu-driven	Yes	Yes	No	Yes
Batch processing	Yes	No	Yes	Yes
User modifications	Yes, source code provided	No	Yes, source code provided	No
Data-set constraints	Yes, modifications possible via source code	Yes	Yes, modification possible via source code	Yes
ASCII output	Yes	Yes	Yes	Yes
Univariate statisitcs	Yes	Yes	Yes	Yes
Additional exploratory capabilities	Yes	Yes	Yes	Yes
Graphical support for analysis	Yes	Yes	Yes	Yes
Transformation	Yes	Yes	Yes	Yes
Back-transformation	No	No	Yes	Yes
Variogram construction	Yes	Yes	Yes	Yes
Variogram analysis	Yes	Yes	Yes	Yes
Variogram graphics	Yes	Yes	Yes	Yes
Cross-validation operations	Yes	Yes	Yes	Yes
Ordinary kriging	Yes	Yes	Yes	Yes
Universal kriging	Yes	No	Yes	Yes
Block kriging	Yes	Yes	Yes	Yes
Indicator kriging	Yes	Yes	Yes	No
Conditional simulation	Perhaps with batch processing	No	Yes	No
Three-dimensional kriging	Perhaps with batch processing	No	Yes	Yes
Mapping	Yes	Yes	Yes	Yes
Contouring	Yes	Yes	Yes	Yes
Gray-scale maps	Yes	Yes	Yes	Yes
Line printer	Yes	No	Yes	Yes
High-resolution screen	No	Yes	Yes via postscript	Yes
High-resolution printer	No	Yes	Yes	Yes
Postscript	No	No	Yes	Yes